Physics and Applications of Photonic Crystals in Semiconductor Lasers

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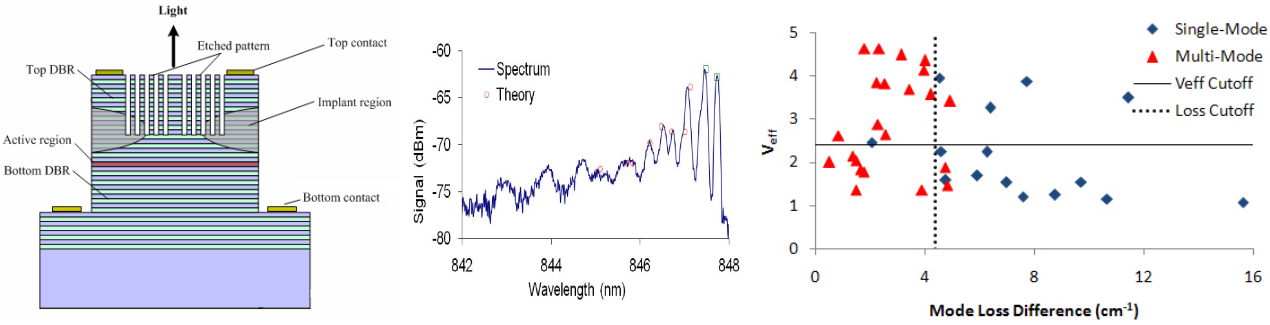
Abstract: Optical confinement from 2-dimensional photonic crystals is shown to enable high performance single mode vertical cavity surface emitting lasers as well as create in-plane novel heterostructure and optimized defect cavity membrane lasers.

Introduction

The 2-dimensional (2D) periodic variation of refractive index achieved with a photonic crystal pattern of air holes can engineer the optical confinement to benefit semiconductor lasers. We show that 2D photonic crystals introduced to vertical cavity surface emitting lasers (VCSELs) can enable single mode emission. A predictive model is used to design single mode lasers based on the optical loss and index modification. Furthermore, combinations of photonic crystals can be introduced to create heterostructures which allow for in-plane confinement and we show optimization can be used to modify perfect periodic structures to increase cavity quality factor in defect membrane lasers.

Photonic Crystal VCSELs

Ion-implanted photonic crystal VCSELs operating at 850 nm have been fabricated and characterized [1-3]. A cross section of the VCSEL structure is shown in Fig. 1(a). A cylindrical waveguide model is used to determine the VCSEL modal properties [3]. The theoretical effects of loss on transverse modes of photonic crystal VCSELs is investigated through finite difference calculations of the Helmholtz equation incorporating a complex index for the lossy photonic crystal cladding regions. The optical loss introduced by the photonic crystals is found from the transverse mode splitting between the fundamental and first higher-order modes as shown in Fig. 1(b) below lasing threshold. By adjusting the complex index in our model, we fit the lowest mode splitting spectrum to determine the optical loss. Note in Fig. 1(b) that resonant wavelengths predicted from our model for higher-order modes agree well with experimental data. Previously, the number of modes has been correlated to a normalized frequency, V_{eff}, which arises from index confinement [2]. We augment this correlation by including the calculated modal loss as shown in Fig. 1(c). For modal loss greater than 5 cm^{-1}, the photonic crystal VCSELs are single-mode regardless of their V_{eff} parameters. Thus optical loss is a significant determination of the lasing modes of a photonic crystal VCSEL.



(a) *(b)* *(c)*

Fig. 1(a) Cross section sketch of implanted photonic crystal VCSEL; (b) below threshold spectrum used to determine loss from photonic crystal; (c) plot of index confinement and optical loss for various photonic crystal designs [3].

Photonic Crystal Membrane Heterostructure Lasers

Two-dimensional photonic crystal membrane lasers have enabled ultra-small modal volumes and high quality factors by using the extremely high reflectivity that a photonic band gap provides [4]. Slow group velocity at the dispersion symmetry points has also enabled band edge lasing [5]. We report the lasing characteristics of a photonic crystal heterostructure laser using a kagome lattice as shown in Fig. 2 [6]. Two different photonic crystal geometries with the same nearest neighbor distance are used to form a relatively large area cavity. The inner kagome lattice that forms the cavity uses less air holes thus provides more gain material for the resonant mode. In Fig. 2(a), the holes in the kagome central region have radii of approximately 0.37a and holes in the outer hexagonal region have radii of approximately 0.32a, where the nearest neighbor hole spacing is a=418 nm. The kagome cavity studied in this work has an area of 36.7 $micron^2$ (approximately 15.3 λ^2) of which approximately 63% is semiconductor. The single mode spectrum under pulsed optical excitation is shown in Fig. 2(b). A lorentzian fit to the emission below threshold gives a

linewidth of approximately 0.64 nm (spectrometer limited), corresponding to a quality factor of about 2400. The photonic crystal heterostructure membrane lasers are under exploration for diode lasers.

Optimized Photonic Crystal Membrane Defect Lasers

The photonic crystal is ideally a periodic pattern of varying refractive index, and thus designs usually exploit Bloch-based analysis. However symmetric, but not periodic, designs are also possible [4]. We report the spectral characteristics and quality factor improvements of a photonic crystal defect cavity laser that has been optimized using the geometric projection method (GPM) [7]. This design approach allows the *shape and position* of the holes to be optimized for a specific laser emission wavelength. Our GPM optimization begins with a design that is optimized for the monopole mode [4], and then improves the reflectivity and thus quality factor by altering the shape of the holes along the perimeter of the defect cavity. The resultant design after 30 optimization iterations are fabricated and the high-fidelity pattern is shown in Fig. 3 (a). Note that the inner holes are no longer circular and are offset from the periodic hole pattern. Lasing spectra from devices from different optimization iterations are measured under pulsed optical excitation. The cavity quality factor measured at 1.1 times threshold improves from 2900 to 3800 (31%) with optimization, as seen in Fig. 3(b). Thus, the GPM is shown to be an effective method for improving the performance of photonic crystal structures leading to more complicated symmetric, but not periodic, refractive index profile [8].

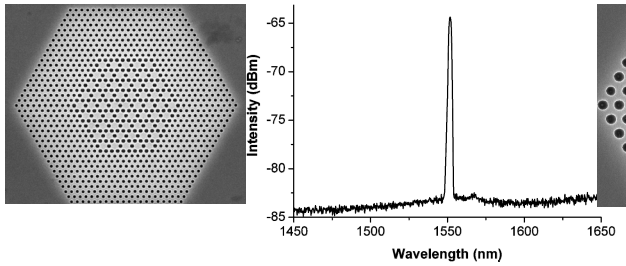


Fig. 2 (a) *Fig. 2(b)*

Fig. 2(a) Heterostructure photonic crystal membrane laser; (b) single mode emission under pulsed optical excitation.

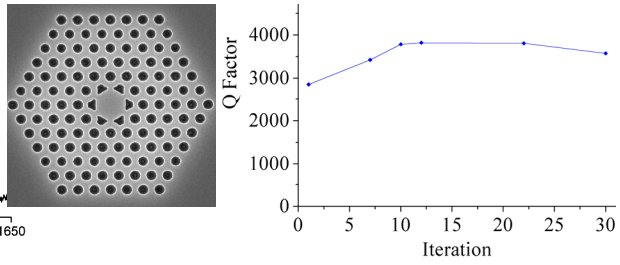


Fig. 3(a) *Fig. 3(b)*

Fig. 3(a) Optimized defect photonic crystal laser. (b) Cavity quality factor improvement versus number of optimization iterations.

Conclusions

2D photonic crystals introduced to either out-of-plane or in-plane lasers can be used to modify both the effective index and optical loss in order to improve laser performance. We have shown examples of high performance photonic crystal VCSELs and photonic crystal membrane lasers that benefit from novel refractive index patterns.

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Kent D. Choquette received B.S. degrees in Engineering Physics and Applied Mathematics from the University of Colorado in 1984 and the M.S. and Ph.D. degrees in Materials Science from the University of Wisconsin in 1985 and 1990, respectively. From 1990–92 he held a postdoctoral appointment at AT&T Bell Labs, Murray Hill, NJ, and from 1993 to 2000 he was a Principal Member of Technical Staff at Sandia National Laboratories in Albuquerque, NM. Since 2000 he is a Professor in the Electrical and Computer Engineering Dept. at the University of Illinois. His Photonic Device Research Group is centered around the design, fabrication, characterization, and applications of vertical cavity surface-emitting lasers (VCSELs), photonic crystal light sources, nanofabrication technologies, and hybrid integration techniques. He has authored more than 200 publications and three book chapters, and has presented numerous invited talks and tutorials. Dr. Choquette has served as an Associate Editor of the *IEEE Journal of Quantum Electronics* and *IEEE Photonic Technology Letters*, and as a Guest Editor of *IEEE Journal of Selected Topics in Quantum Electronics*. He is a Fellow of the IEEE, a Fellow of the Optical Society of America, and a Fellow of SPIE.